EOS VALIDATION INVESTIGATION FINAL REPORT
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Submitted to:

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Title: A Study of Uncertainties for MODIS Cloud Retrievals of Optical Thickness and Effective Radius

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I. FUNDING SUMMARY AND GRANT STATUS

As of September 1998, grant monies for the portion of the investigation performed by R. Pincus have been sent directly to the co-P.I. S. Platnick remains P.I. for the overall investigation. The UMBC grant (Platnick) expired in December 2001; the NOAA-CIRES grant (Pincus) expires at the end of March 2003. This final report covers the final year of the UMBC grant and the portion of the NOAA-CIRES grant up through end of 2002.

II. REPORT SUMMARY

The investigation spanned four linked components as summarized in section III, each relating to some aspect of uncertainty assessment in the retrieval of cloud optical and microphysical properties using solar reflectance algorithms such as the MODIS operational cloud product (product IDs MOD06, MDY06 for Terra and Aqua, respectively). As discussed below, three of these components have been fully completed (items (1), (2), and (3) in the next section) while item (4) has been partially completed. These efforts have resulted in peer-reviewed publications and/or information delivered to the MODIS P.I. (M. D. King) for inclusion in the cloud product Quality Assessment (QA) output, a portion of the product output used, in part, for retrieval error assignments.

This final report begins with a synopsis of the proposed investigation (section III) followed by a summary of work performed up through the last report including updates (section IV). Section V describes new activities. Publications from the efforts are listed in section VI. Figures (available in powerpoint format) are found in section VII.

III. PROPOSED INVESTIGATION

Use model calculations, along with analysis of MODIS and MODIS Airborne Simulator (MAS) data, to assess the accuracy of the MODIS Cloud Product retrievals of liquid water cloud optical thickness and effective radius. Investigation to include:

(1) Assessment of library errors: assess errors in the computation of reflectance and emission libraries used in the retrieval algorithm. Include such factors as wavelength integration, cloud droplet size distribution assumptions, complex index of refraction of water, etc.

(2) Effect of instrument uncertainty and atmospheric corrections: examine the uncertainty produced by imperfect knowledge of the retrieval environment, including instrument performance and above-cloud atmospheric effects.

(3) Effect of vertical inhomogeneity: investigate effects of vertical stratification in droplet size on retrieved optical properties, especially discrepancies between retrieved effective radii made from reflection measurements in different near-IR bands.

(4) Effect of horizontal inhomogeneity: determine the uncertainties and biases due to horizontal inhomogeneity in cloud optical properties, and develop a theoretical framework for using image spatial variability to estimate pixel level uncertainty. Results will provide quantitative guidance for the assessment of quality assurance parameters for the MODIS cloud retrieval algorithm.

IV. SUMMARY OF ACTIVITIES IN PREVIOUS YEARS

A. Investigation approach and sensitivity libraries:

All four of the efforts mention in section III make use of sensitivity calculations for uncertainty assessment. In turn, the sensitivities are derived directly from the forward radiative transfer calculations (libraries) using in the retrieval algorithm, and as such are compatible with any specific library-based retrieval implementation.

The MODIS libraries, calculated for water-absorbing (1.6, 2.1, and 3.7 μm) and nonabsorbing (0.65, 0.86 μm) bands, are used to infer cloud optical thickness (τ), effective radius (r_e), and liquid water path (derived from the latter two quantities). These modeled cloud reflectances span the expected range of optical thickness, effective radius, and solar and viewing geometry. Since combinations of two spectral bands are used simultaneously in the MODIS algorithm, sensitivities involve two partial derivatives of reflectance with respect to both optical thickness and effective radius, i.e.,

$$\left.\frac{\partial\tau}{\partial \ln R_{0.65}}\right)_{R_{2.1}=const.}, \quad \left.\frac{\partial r_e}{\partial \ln R_{2.1}}\right)_{R_{0.65}=const.}$$

$$\left.\frac{\partial\tau}{\partial \ln R_{2.1}}\right)_{R_{0.65}=const.}, \quad \left.\frac{\partial r_e}{\partial \ln R_{0.65}}\right)_{R_{2.1}=const.}$$

These derivatives give retrieval *sensitivity* to errors in either library calculations (modeling errors such as cloud model, radiative transfer code, etc.) or reflectance measurements (instrument calibration, atmospheric corrections, etc.), directly addressing the first two items of section III. The above equations were formulated for calculation directly from reflectance libraries (constant τ and r_e grid) and have been calculated for a subset of library τ, r_e, and angles (see **Fig. 1**). The calculations thus constitute a **sensitivity library** for direct use by the MODIS algorithm or similar algorithms. An example was given in the last report.

As with any uncertainty estimate based on sensitivity calculations, it is assumed that errors are small perturbations about a linear region of the solution space. For bias errors (e.g., calibration, model), the sensitivities are useful for both gridded, aggregated statistics (MODIS Level-3) as well as pixel-level retrievals. The application to random errors is only meaningful for pixel-level retrievals since gridded, aggregated data will tend to reduce random errors to zero (quantitatively assessed from second-order partial derivatives).

An initial analysis of these sensitivity libraries was made in the previous reporting period. At that time, a first look at sensitivity was made as a function of geometry. More recent analysis using MODIS geometry and data is presented in section V (see **Figs. 2-5**).

B. Cloud heterogeneity

The MODIS cloud retrieval algorithm provides effective plane-parallel values of optical thickness and effective radius that give rise to the measured spectral reflectances. The physical meaning or use of these retrievals therefore depends on the degree to which real clouds are plane-parallel-like. One source of cloud modeling error is therefore the radiative effect of cloud inhomogeneities (vertical and horizontal). The sensitivity libraries can be used to assess retrieval errors arising from small departures of real cloud radiance fields from plane-parallel models. With respect to items (3) and (4) above:

<u>Investigation item (3): effect of vertical inhomogeneity</u>

S. Platnick finished developing a theoretical framework for assessing the influence of a cloud droplet size profile on the three separate size retrievals available from the MODIS shortwave infrared bands (droplet size is currently inferred separately from each of the 1.6, 2.1, and 3.7 µm bands, in conjunction with a non-absorbing water band such as the 0.86 µm band). Preliminary results were summarized in the previous report. In general, theory suggests that differences between 1.6 and 2.1 µm size retrievals are likely to be within expected retrieval uncertainty (< 1 µm) for single layer, adiabatic clouds, while 3.7 µm size retrievals are likely to be significantly larger (> 1 µm).

A discussion of the theory and results has now been published [*Platnick*, 2000]. The latest MODIS results have generally verified the expected adiabatic relationships [*Platnick et al.*, *TGARS Aqua special issue*, 2003 (in press)] as have MODIS Airborne Simulator (MAS) studies [*Platnick et al.*, 2000; *Platnick et al.*, 2001]. Comparison between individual MODIS size retrievals may serve as a means of assessing retrieval QA and/or inferring multilayer, 3-dimensional, or other cloud types/effects.

<u>Investigation item (4): effect of horizontal inhomogeneity</u>

Stochastic cloud models:

The impact of cloud top height/structure on retrievals was assessed with a stochastic cloud model developed by R. Pincus. Reflected radiation in the MODIS retrieval bands was calculated for the modeled cloud fields with a three-dimensional radiative transfer code (SHDOM). Results were then compared with plane-parallel models via the sensitivity libraries discussed above. Initial results indicated that 3-D effects in unbroken Sc boundary layer clouds are about the same size as other retrieval uncertainties (e.g., calibration), but have a strong directional signature, with large effects at low sun angles near direct forward- and back-scattering directions. Sensitivities are also large at these geometries, so that retrievals may be strongly affected.

The original plan was to perform thorough uncertainty analyses using SHDOM by varying parameters in the stochastic cloud. This turned out to be computationally prohibitive, and Monte Carlo techniques are probably better suited. As part of the I3RC effort, R. Pincus is developing a Monte Carlo code for radiance calculations, and expects to revisit this question when the radiative transfer models have improved.

Estimates of horizontal transport:

S. Platnick developed a photon diffusion approximation for the root-mean-square horizontal transport of reflected and transmitted photons through a cloud. Preliminary results, summarized in the previous progress report, provide a simple means for assessing the horizontal spatial scale over which cloud retrievals are effectively averaged. Calculations have been made for a variety of cloud thicknesses, effective radii, and angles. This simple theory (results of which could be saved in a library similar to the sensitivity calculations above) might provide a quantitative means for recognizing 3-dimensional cloud effects on reflectance variability at the smallest MODIS spatial scales (0.25 km). Since the last reporting period, a paper describing the theory and giving results for pertinent cloud remote sensing spectral bands was published [*Platnick*, 2001a, 2001b].

V. Activities since the last reporting period

In addition to the publications discussed in section IV, the following analyses were undertaken:

A. Retrieval Sensitivities

An evaluation of sensitivities for the MODIS geometry has been made. Examples are shown in **Figs. 2-5**.

For a fixed cloud (τ, r_e), sensitivities are a function of solar/viewing geometry. The resulting PDFs of geometric angles therefore determine the PDF of sensitivities. Further, the distribution of geometric parameters (μ, μ_0, ϕ) in any given latitude bin is determined by the spacecraft orbit and sun synchronous time. The two primary sensitivity PDFs for the Terra orbit on 21 December (NH winter solstice) are shown in **Fig. 2** as a function of latitude for a water cloud with τ=10, r_e=10 µm. Averaging these PDFs over latitude bins and assuming a 5% bias in instrument calibration and/or model error gives the error plots shown in **Fig. 3**. Interestingly, on this day a relative peak in error is seen at a latitude of about -25°. Error increases towards both poles due to larger solar zenith angles.

There is of course a PDF of τ, r_e that must be folded into to any realistic example. Such calculations were done for MODIS Terra data from 18 July 2001. The granule-level example of **Fig. 4** shows absolute error in τ and r_e for marine Sc clouds off the coasts of Peru/Chile assuming that calibration bias in the 0.86 and 2.1µm bands are 3% relative and of opposite signs (worse case correlation). It is seen that $\Delta\tau$~3-5 along coastal areas while Δr_e is generally a micrometer or less. For comparison, the retrieved parameters for this cloud field is about τ~20, r_e~9 µm (though highly variable). A global (MODIS Level-3) from the same day is shown in **Fig. 5** for the same calibration error assumption; both retrievals and relative error are shown.

Since the time this work was done (late 2001, early 2002), the MODIS operational cloud retrieval code has been greatly improved (e.g., polar retrievals, atmospheric corrections, surface effects, etc). The latest MODIS code (referred to in the data system as "collection 004") is being used to reprocess all of Terra data as well as forward Aqua processing. The new code also allows specific retrieval effects such as atmospheric corrections to be isolated. Application of the sensitivity libraries to the improved MODIS retrievals is pending subject to resources and other priorities within the MODIS retrieval group. It is anticipated that a publication can be submitted after initial application into a research version of the updated MODIS code.

B. MODIS validation field campaign, SAFARI 2000

Over the course of the 4th year of the grant, S. Platnick was involved in analysis of relevant Southern Africa Fire Atmosphere Research Initiative (SAFARI-2000) data sets and attended several science team meetings with validation grant money.

A MODIS cloud and aerosol validation experiment was planned in conjunction with the SAFARI dry season campaign in August-September 2000. During the last 10 days of the campaign, the UW CV-580 was re-deployed from central continental regions to Walvis Bay, Namibia for the purpose of studying marine stratocumulus clouds off the coast of Namibia. During this time, the UK C130 flew out of Windhoek, Namibia in partial support of this effort. The Namibian marine cloud system is similar in principle to the better known California stratus regime. However, preliminary AVHRR retrievals (Platnick et al., *ISRSE* 2000) suggest relatively small droplet sizes in comparison, possibly indicative of significant CCN sources.

The goal of the cloud validation included (a) comparisons with *in situ* measurements, (b) MAS retrievals, and (c) characterization of the Namibian stratocumulus regime. S. Platnick was involved in each of these efforts. Items (a) and (b) are nearing completion. The results are rather equivocal for several reasons. First, due to meteorology and aircraft issues, there is only a single MODIS/MAS cloud validation opportunity with the CV-580 (which had to leave the field early). Fortunately, UK C-130 cloud observations added several more opportunities. To date, MODIS droplet size retrievals (using latest production code from fall '02) appear to be biased high by several micrometers compared with FSSP analysis. MODIS comparisons with MAS retrievals show agreement on one day but are larger than MAS retrievals on a second day. Temporal differences between MODIS and MAS observations of the same cloud region are likely an extenuating factor. The analysis is being prepared for publication.

C. Anticipated Activities in Final Months

A paper documenting the retrieval sensitivities and their application to pixel-level and aggregated estimates of uncertainty lacks only final figures, and should be submitted by the end of the grant period.

D. Interaction with the MODIS Atmosphere Science team

Both investigators have continued to work closely with various members of the MODIS atmosphere science team, and will continue to do so after the grant terminates in early 2003. The involvement will include implementation of retrieval uncertainty look up tables for MODIS cloud optical and microphysical QA (processed as part of MOD06, MYD06) at the discretion and resources of the P.I. (M. D. King), and participation in validation field activities (including CRYSTAL-FACE experiment from July 2002). S. Platnick is an associate member of the MODIS atmosphere team.

VI. PUBLICATIONS:

Peer-reviewed publications directly resulting from investigation funded activities include:

Pincus, R., S. A. McFarlane, S. A. Klein, 1999: Albedo bias and the horizontal variability of clouds in subtropical marine boundary layers: Observations from ships and satellites J. Geophys. Res., **104**, 6183-6191.

Platnick, S., M. D. King, H. Gerber, P. V. Hobbs. 2001: A solar reflectance technique for cloud retrievals over snow and ice surfaces. *J. Geophys. Res.*, **106**, 15,185-15,199.

Platnick, S., 2001a: A superposition technique for deriving photon scattering statistics in plane-parallel cloudy atmospheres. *JQSRT*, **68**, 57-73.

Platnick, S., 2001b: Approximations for horizontal transport in cloud remote sensing problems. *JQSRT*, **68**, 75-99.

Platnick, S., 2000: Vertical photon transport in cloud remote sensing problems. *J. Geophys. Res.*, **105**, D18, 22,919.

Platnick, S., P. A. Durkee, K. Nielsen, J. P. Taylor, S-C. Tsay, M. D. King, R. J. Ferek, P. V. Hobbs, and J. W. Rottman, 2000: The role of background cloud microphysics in the radiative formation of ship tracks. *J. Atmo. Sci.*, **57**, 2607-2624.

King, M. D., S. Platnick, C. C. Moeller, H. Revercomb, D. A. Chu, 2003: Remote Sensing of Smoke, Land and Clouds from the NASA ER-2 during SAFARI 2000. *J. Geophys. Res.*, submitted.

Conference presentations related to the investigation:

Platnick, S., et al, SAFARI 2000 Data Synthesis Workshop, 7-11 October 2002, Charlottesville VA.

Platnick, S., et al., SAFARI 2000 First Data Workshop, Siavonga, Zambia, 28-31 August 2001.

Platnick, S., S. A. Ackerman, R. A. Frey, and M. D. King: Remote sensing of Namibian stratocumlus clouds, *28th International Symposium on Remote Sensing of the*

Environment, 27-31 March 2000, Cape Town, South Africa.

Platnick, S., M. D. King, S. Tsay, G. T. Arnold, H. Gerber, P. V. Hobbs, A. Rangno, 1999: A technique for cloud retrievals over snow and ice surfaces: results from FIRE-ACE, *AMS 10th Conference on Atmospheric Radiation*, 28 June - 2 July, Madison WI.

Pincus, R., A. Marshak, S. Platnick, and M. Gunshor, 1999: "Assessing the importance of cloud top topography on remote sensing retrievals", *AGU Spring Meeting*, 1-4 June, Boston MA.

Platnick, S., J. Li, M. D. King, S. Tsay, G. T. Arnold, M. Gray, P. V. Hobbs, A. Rangno, 1999: Cloud bidirectional reflectance measurements of arctic stratus during FIRE-ACE. *ALPS 99 Symposium*, January 18-22, Meribel, France.

VII. FIGURES (all available in powerpoint format)

For a **plane-parallel cloud** geometry, the ***measured*** reflection quantities in a non-absorbing and absorbing band (e.g., visible and near-IR band, respectively) are described functionally as:

$$R_{\lambda_1}(\tau, r_e, \mu, \mu_0, \phi) = R_1$$

$$R_{\lambda_2}(\tau, r_e, \mu, \mu_0, \phi) = R_2$$

with τ, r_e constituting the ***retrievals***. The **sensitivities** are defined as:

$$\left.\frac{\partial\tau}{\partial R_1}\right)_{R_2\,\mathrm{const}}, \left.\frac{\partial\tau}{\partial R_2}\right)_{R_1\,\mathrm{const}}, \left.\frac{\partial r_e}{\partial R_1}\right)_{R_2\,\mathrm{const}}, \left.\frac{\partial r_e}{\partial R_2}\right)_{R_1\,\mathrm{const}}$$

where,

$$\left.\frac{\partial\tau}{\partial R_1}\right)_{R_2} = \left[\left.\frac{\partial R_1}{\partial\tau}\right)_{r_e} - \left.\frac{\partial R_1}{\partial r_e}\right)_{\tau} \frac{\left.\frac{\partial R_2}{\partial\tau}\right)_{r_e}}{\left.\frac{\partial R_2}{\partial r_e}\right)_{\tau}}\right]^{-1} \quad \text{etc., ...}$$

Fig. 1. Summary of sensitivity definitions and an example formulation based on reflectance libraries at constant τ and r_e. Over the ocean, bands 1 and 2 for MODIS are typically the 0.86 µm and 2.1 µm bands, respectively.

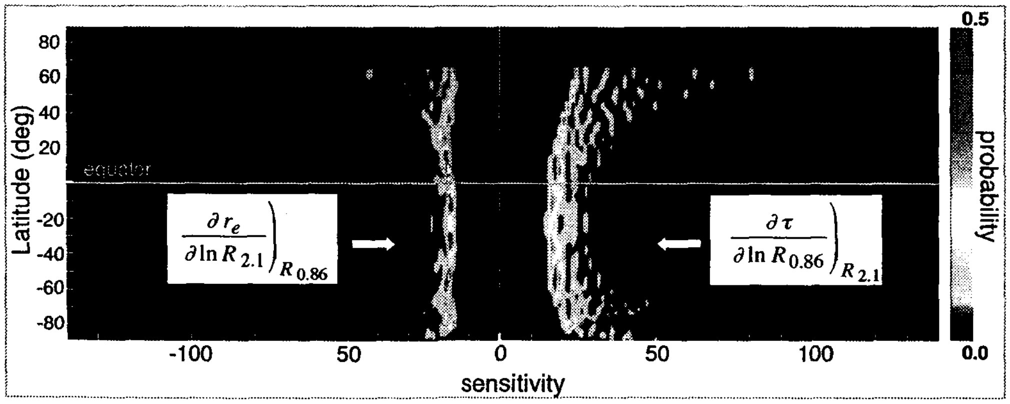

Fig. 2. Probability distribution for the two primary sensitivities as a function of latitude (calculated assuming τ=10, r_e=10 µm, and a Terra orbit on 21 December). Sensitivity, and therefore retrieval uncertainty, is seen to be latitude and hemispheric dependent.

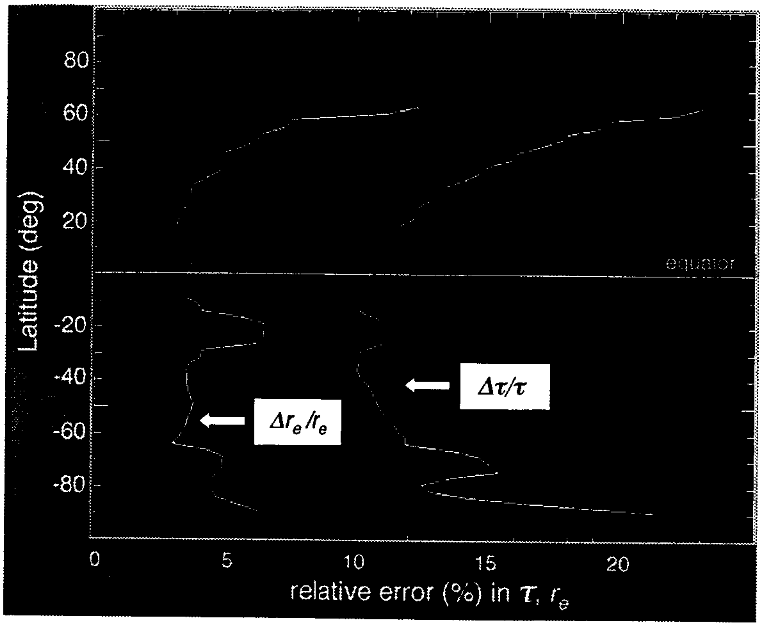

Fig. 3. Overall absolute value of the error resulting from a 5% relative calibration bias as a function of latitude, averaged over the PDFs of Fig. 2.

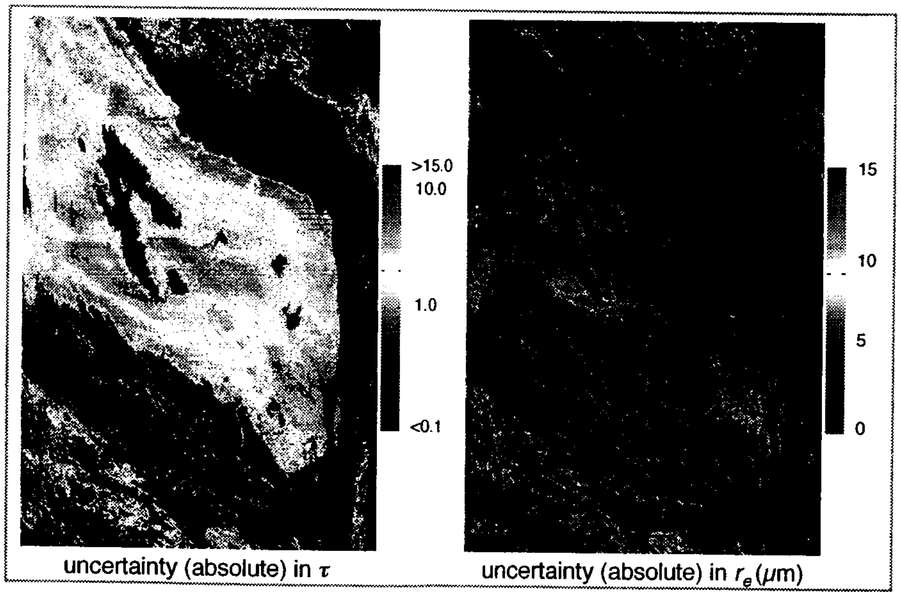

Fig. 4. Example granule-level retrieval uncertainty for water clouds resulting from a relative calibration bias of +3% and –3% for MODIS bands 1 (0.86 μm) and 7 (2.1 μm), respectively. Granule is of marine boundary layer Sc off the coast of Peru on 18 July 2001.

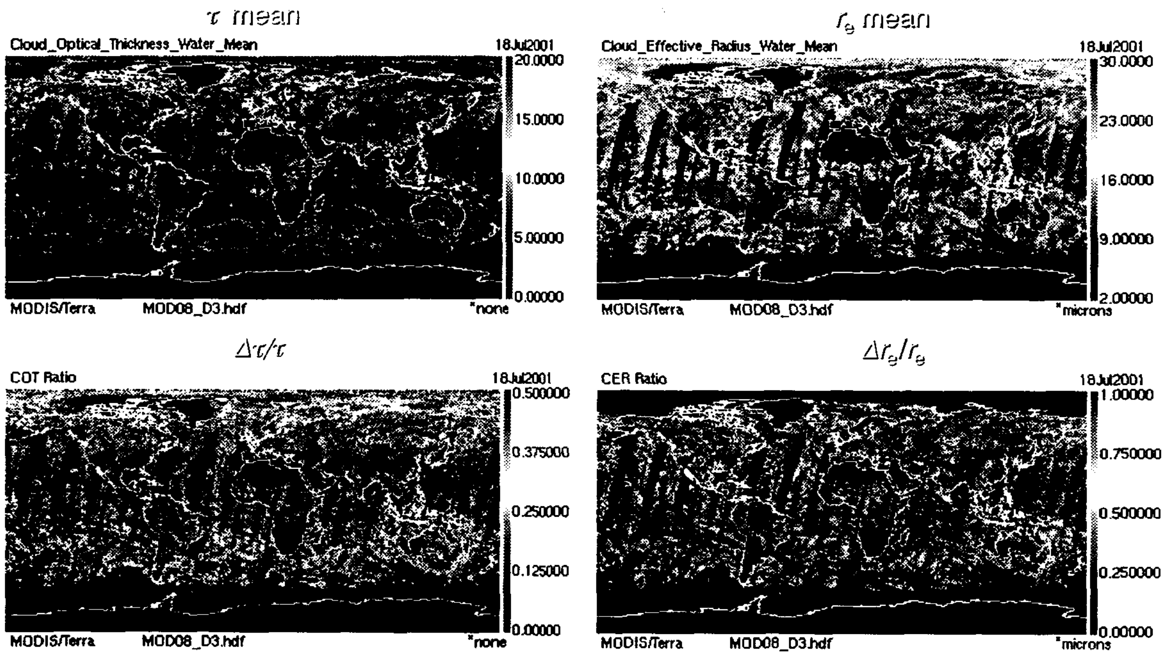

Fig. 5. Example global Level-3 daily retrieval uncertainty for water clouds resulting from a relative calibration bias of +3% and –3% for MODIS bands 1 (0.86 μm) and 7 (2.1 μm), respectively, on 18 July 2001.